ISSN: 2836-3655
DOI: 10.33552/AHM.2026.03.000620
Advances in Hydrology & Meteorology
Iris Publishers

Mini Review

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Dissolved Gas Resources in Deep Aquifers: Rethinking Subsurface Exploration in the Energy Transition

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Received Date: November 19, 2026

Published Date: November 25, 2026

Introduction

For more than a century, natural gas exploration has primarily focused on identifying geological structures capable of trapping significant volumes of free gas. Conventional petroleum exploration has therefore been driven by the search for specific geological configurations involving source rocks, migration pathways, reservoir formations and impermeable seals. More recently, unconventional resources, including shale gas and coalbed methane, have expanded this exploration paradigm by targeting gas retained within low-permeability formations or coal seams. Nevertheless, the underlying exploration strategy has largely remained focused on identifying concentrated gas accumulations. An alternative approach deserves greater attention: the exploration and potential exploitation of gases dissolved in subsurface groundwater. Methane, carbon dioxide, hydrogen, helium and other geological gases can occur in dissolved form within sedimentary aquifers and deep formation waters. Their occurrence is controlled by geological, geochemical and hydrodynamic processes, including gas generation, dissolution, migration, water-rock interactions and fluid circulation.

Dissolved Methane: An Already Documented but Underexploited Resource

Numerous studies have documented the widespread occurrence of dissolved methane in groundwater. Investigations in Alberta [1], Great Britain [2], and the Great Artesian Basin in Australia [3] demonstrate that methane is present in many aquifer systems, with concentrations and origins varying considerably according to geological and hydrogeological settings. Both microbial methanogenesis and thermogenic processes contribute to these occurrences. Particularly significant concentrations have been reported in deep Australian aquifers, reaching up to approximately 31 mg/L of dissolved methane [3]. Furthermore, the Minami-Kanto gas field in Japan provides an example of a gas-producing system in which methane is predominantly dissolved in formation water [4]. These observations demonstrate that groundwater can constitute a significant carrier and storage medium for natural gas, rather than simply being an associated fluid in conventional hydrocarbon reservoirs.

Dissolved Natural H_2 and Helium: New Opportunities Associated with the Energy Transition

The same approach could be extended to gases of growing strategic importance. Natural hydrogen represents a particularly promising example. Although exploration has initially concentrated on surface emissions and conventional gas accumulations, recent investigations have demonstrated the presence of substantial dissolved hydrogen in deep aquifers. The Bourakébougou field in Mali provides an illustrative example, with hydrogen occurring both as free gas in shallow reservoirs and predominantly in dissolved form in deeper water-bearing formations [5]. In Lorraine, the REGALOR research programme has also contributed to demonstrating the presence of significant concentrations of natural hydrogen dissolved in Carboniferous aquifer waters [6] with a dissolved H_2 concentration of 4 mg/L at a depth of 1300 m in the

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Fols-1a borehole. This concentration increases with depth and could reach 30 mg/L at a depth of 3000 m. These results open new perspectives for understanding hydrogen generation, migration and preservation in sedimentary basins.

Recently, the Australian company Golden Hydrogen announced a dissolved H_2 concentration of approximately 40 mg/L in the Ramsay 3 borehole on the Yorke Peninsula [7]. Other strategic gases, particularly helium, can also accumulate in groundwater through the transfer of radiogenic gases from basement rocks and sedimentary formations. Groundwater therefore represents a potentially important geochemical reservoir for several gases of economic interest [8].

Depth-Dependent Gas Solubility in Groundwater Systems

The solubility of gases in groundwater is strongly influenced by the pressure and temperature conditions prevailing within aquifers. With increasing burial depth, hydrostatic pressure generally rises by approximately 10 MPa per kilometre, favouring the dissolution of gaseous compounds in water and potentially increasing the dissolved gas storage capacity of deep aquifers. However, this pressure effect is partly counterbalanced or increased by the geothermal gradient by approximately 30°C per kilometre. Salinity also plays a significant role, generally decreasing gas solubility through the salting-out effect. Carbon dioxide (CO_2) exhibits substantially higher aqueous solubility and additional chemical interactions through the carbonate system, making its behaviour particularly sensitive to pH and water composition. By contrast, hydrogen (H_2), methane (CH_4) and Helium (He) are not affected by chemical fingerprint of water. Nevertheless, the pressure dependence of gas dissolution suggests that deep aquifers may represent an extensive and still insufficiently investigated domain for the storage and potential recovery of naturally occurring gases.

Towards a Distributed-Resource Exploration Strategy

The main conceptual difference between conventional gas exploration and dissolved gas exploration lies in the nature of the target. Conventional exploration seeks relatively localized accumulations of free gas, requiring favourable trapping conditions. In contrast, dissolved gas exploration could target extensive aquifer systems in which gases are distributed throughout large volumes of groundwater. This approach potentially offers access to geological resources that are more widely distributed than conventional gas accumulations. However, a large geographical distribution does not automatically imply economically recoverable resources. Gas concentrations, aquifer productivity, groundwater volumes, extraction rates and gas separation efficiency will determine the actual potential of each system. The main technological challenge will therefore be to develop efficient methods for recovering dissolved gases, including controlled degassing, membrane separation and potentially integrated gas-water processing systems. The energy required for pumping and separation, together with the management or reinjection of produced water, will be critical parameters in assessing the environmental and economic viability of such operations. Innovative technologies, as in-situ membrane separation proposed by the REGALOR project, must be promoted. They reduce energy request and does not require water production and management.

Conclusion

The increasing demand for low-carbon energy and strategic gases calls for a broader understanding of geological gas resources. Rather than exclusively targeting naturally concentrated gas accumulations, future exploration could progressively consider the much larger volumes of groundwater circulating and residing within sedimentary basins and crystalline formations. This does not imply replacing conventional gas exploration, but rather complementing it with a new approach based on the identification, characterization and potential recovery of dissolved gases. The transition from localized gas accumulations towards more widely distributed dissolved gas resources could therefore represent an important evolution in the way geological resources are explored and potentially exploited.

Dissolved gases have long been known, but their exploitation as primary resources remains a much less developed prospect. This requires:

a) A shift from a “geology of traps” to a “geology of flows”—moving beyond the search for locations where gases have accumulated to also examining the hydrogeological systems in which they are produced, transported, and dissolved; and

b) A shift from a concentrated resource to a distributed one. The total quantity of potentially recoverable gas could be substantial across large sedimentary basins, even if the concentrations at any given point are low.

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